

Birth and Evolution of Isolated Radio Pulsars

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Abstract. We investigate the birth and evolution of isolated radio pulsars using a population synthesis method, modeling the birth properties of the pulsars, their time evolution, and their detection in the Parkes and Swinburne Multibeam (MB) surveys. Together, the Parkes and Swinburne MB surveys [1, 2] have detected nearly 2/3 of the known pulsars and provide a remarkably homogeneous sample to compare with simulations. New proper motion measurements [3, 4] and an improved model of the distribution of free electrons in the interstellar medium, NE2001 [5], also make revisiting these issues particularly worthwhile. We present a simple population model that reproduces the actual observations well, and consider others that fail. We conclude that: pulsars are born in the spiral arms, with the birthrate of 2.8 ± 0.5 pulsars/century peaking at a distance ~ 3 kpc from the Galactic centre, and with mean initial speed of 380^{+40}_{-60} km s $^{-1}$; the birth spin period distribution extends to several hundred milliseconds, with no evidence of multimodality, implying that characteristic ages overestimate the true ages of the pulsars by a median factor >2 for true ages $<30,000$ yr; models in which the radio luminosities of the pulsars are random generically fail to reproduce the observed $P - \dot{P}$ diagram, suggesting a relation between intrinsic radio luminosity and (P, \dot{P}) ; radio luminosities $L \propto \sqrt{\dot{E}}$ provides a good match to the observed $P - \dot{P}$ diagram; for this favored radio luminosity model, we find no evidence for significant magnetic field decay over the lifetime of the pulsars as radio sources (~ 100 Myr).

Keywords: Pulsars, radio, population, evolution

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INTRODUCTION

From soon after the discovery of the pulsars [6], their Galactic population has been the focus of numerous studies [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. Nevertheless, in spite of much progress, many outstanding questions remain. What are the birth positions, velocities, spin periods, and magnetic fields of the pulsars? How do these evolve in time and how are they related to the radio luminosities of the pulsars? One approach to answering these questions is to make use of the statistical power of the growing pulsar catalogue to study the pulsar population as a whole.

Many recent advances in pulsar astronomy make it particularly worthwhile to revisit the above questions through population synthesis. The recently completed Parkes and Swinburne Multibeam (PMB and SMB; [1, 2]) surveys have detected nearly 2/3 of the known pulsars and provide a large and remarkably homogeneous observed sample to compare with simulations. New proper motion measurements [3, 4] and an improved model of the interstellar medium [5] also provide valuable new information.

In this work, the details of which have been reported by Faucher-Giguère & Kaspi (2006) [21], we investigate the birth properties of Galactic isolated radio pulsars and their time evolution. To do so, we generate an ensemble

of mock galaxies populated by pulsars with prescribed birth properties (spatial locations, velocities, spin periods, radio luminosities, magnetic fields) and evolve the pulsars in time using physical models. We model the selection function of the PMB and SMB surveys using a modified version of the radiometer equation [22] and apply it to our mock galaxies. We compare the observed histograms of Galactic longitudes, latitudes, dispersion measures, 1.4 GHz radio fluxes, pulse periods, magnetic fields, as well as the observed $P - \dot{P}$ diagrams, to judge how well each population model reproduces the actual observations.

RESULTS

In Figure 1, we compare the $P - \dot{P}$ diagram for the pulsars detected in the PMB and SMB surveys with the corresponding diagrams in our best simulation with radio luminosities $L \propto \sqrt{\dot{E}}$ and with a simulation in which the radio luminosities of the pulsars are uncorrelated with their other characteristics (“random”). In Figure 2, we compare the histograms of Galactic longitudes, latitudes, dispersion measures, 1.4 GHz radio fluxes, pulse period, and magnetic fields obtained in our best simulation with the actual observations. In what follows, we summarize the key results obtained from our preferred model and its comparison with various alternatives.

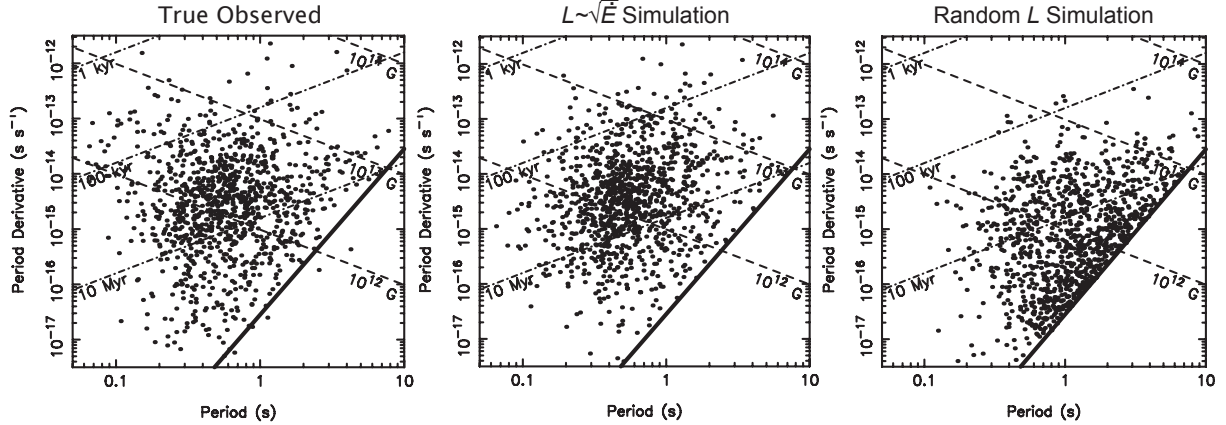


FIGURE 1. Comparison of the $P-\dot{P}$ diagram for the pulsars detected in the Parkes and Swinburne Multibeam surveys (left) with the corresponding diagrams in our best simulation with $L \propto \sqrt{E}$ (middle) and with a simulation in which the radio luminosities of the pulsars are uncorrelated with their other characteristics (“random”; right). While the simulation with $L \propto \sqrt{E}$ reproduces the observed diagram remarkably well, the model with random radio luminosities produces a pile-up of pulsars near the death line that is in clear disagreement with the observations.

We find that pulsars are born at a rate of 2.8 ± 0.5 per century in the Galaxy, with the rate peaking a distance of ~ 3 kpc from the Galactic centre (in agreement with [23, 24]), and a mean velocity of 380^{+40}_{-60} km s $^{-1}$. In particular, models in which the pulsar birthrate peaks at the Galactic centre or is uniform throughout the Galactic disk, as is frequently assumed (e.g., [15, 18]), fail to reproduce the observed distribution of Galactic longitudes. We further find evidence that the pulsar birthrate traces the Galactic spiral arms, as expected if pulsars are formed in core collapse supernovae marking the death of short-lived massive stars.

The birth spin period distribution extends to several hundred milliseconds, with no evidence of multimodality. As a consequence, the assumption that $P/P_0 \ll 1$ is violated for many young pulsars and the characteristic age $t_{\text{char}} \equiv P/2\dot{P}$ is an overestimate of the true age of a pulsar by a median factor > 2 for true ages $< 30,000$ yr. This is consistent, for example, with PSR J1811–1925 having a characteristic age $\sim 12\times$ the age inferred from its association with the supernova remnant G11.2 – 0.3 (AD 386; [25, 26]).

Models in which the pulsar radio luminosities, L , are randomly assigned to pulsars generically predict too many pulsars detected away from the Galactic plane and a clear pile-up on the death line in the $P-\dot{P}$ diagram that is not observed (Fig. 1). This suggests a relation between a pulsar’s intrinsic radio luminosity and its (P, \dot{P}) which favors the detection of young pulsars, as was often assumed in previous analyses (e.g., [15]).

We find that $L \propto \sqrt{E}$ naturally solves both issues by uniformly dimming the pulsars as they age and approach the death line.¹

Finally, in contrast with previous studies following a similar methodology (e.g., [19, 20]), we do not find evidence for significant magnetic field decay over the lifetime of pulsars as radio sources (~ 100 Myr). Indeed, we have throughout our study *assumed* that the magnetic fields of our mock pulsars were constant in time and were able to obtain good agreement for our best model in which $L \propto \sqrt{E}$ between the simulations and the real pulsars (Fig. 1, 2). We caution, however, that this does not constitute a proof of that pulsar magnetic fields are constant. Rather, much of the success of our favored model lies in the chosen radio luminosity dependence on P and \dot{P} and it is possible that another choice would produce similar agreement. In the absence of an independently determined luminosity model, we must regardless conclude that pulsar population synthesis studies currently do not *require* any decay of pulsar magnetic fields.

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¹ In this model, the radio luminosity contours are parallel to the death line.

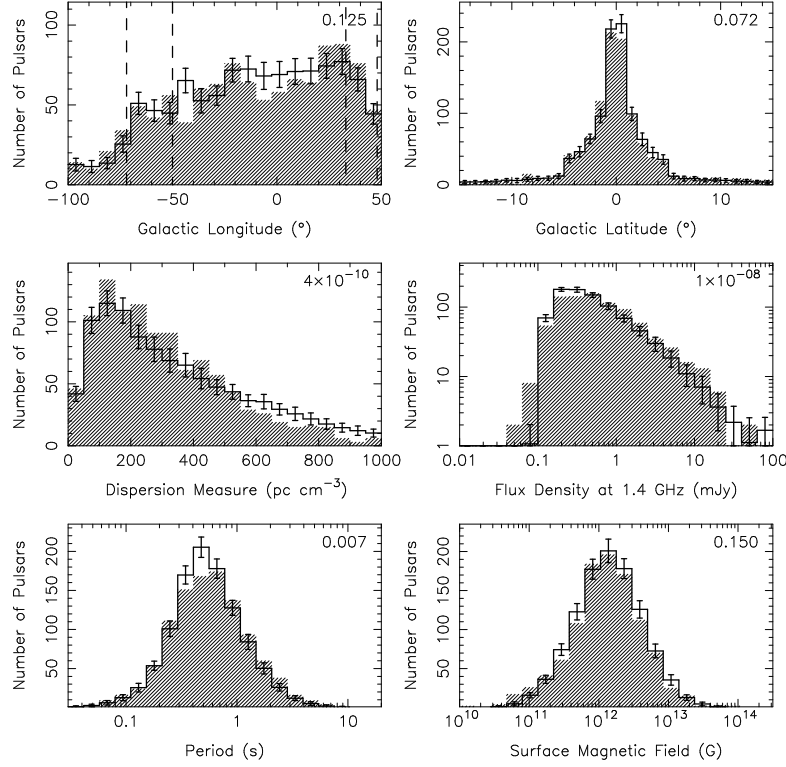


FIGURE 2. Distributions of observed pulsar Galactic longitudes and latitudes, dispersion measures, flux densities at 1.4 GHz, pulse periods, and surface magnetic fields for our best model with $L \propto \sqrt{E}$ (solid lines) compared to the real distributions (hatched histograms).

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